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Microwave absorption, using the co-planar waveguide configuration that we developed earlier, was employed to investigate electron dynamics of the high mobility 2D charge carriers in $GaAs/Al_xGa_{1-x}As$ heterostructures. Three experiments were carried out:

(1) Dynamic response of composite fermions in an anti-dot lattice
(2) Observation of microwave induced cyclotron harmonics, and
(3) Investigation of pinning of the Wigner crystal and measurement of the crystal correlation lengths as a function of carrier density.

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"Probing 2D Physics with Microwave"

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October 17, 2003

1. WORK ACCOMPLISHED – Three experiments were completed

1.1 Dynamic response of composite fermions in an anti-dot lattice

The ground state of the strongly interacting 2D electron gas in a B filed at half-filling of the lowest Landau level (i.e. filling factor $\nu = \frac{1}{2}$) is a Fermi liquid of composite fermions (CF's), each can be thought of as an electron bound to two flux quanta. These bizarre particles feel no net B filed at $\nu = \frac{1}{2}$ and the two series of Fractional Quantum Hall Effect (FQHE) states at $\nu = p/(2p \pm 1)$, with p = integers, can be viewed as the integer Quantum Hall Effect of the CF's resulting from the Landau quantization of their kinectic energy by the effective B they feel away from half-filling. We have studied the microwave response of the CF's in uniform samples and in samples fabricated with anti-dot arrays. We find that, in samples with anti-dot arrays, the ac conductivity increases strongly with increasing microwave frequency, strongest at $\nu = \frac{1}{2}$ and clearly observed in the entire CF Landau quantization region of the $\nu = p/(2p \pm 1)$ FQHE series.

This frequency dependence is contrary to expectation for ordinary metallic systems and is not observable for $T \geq 600$ mK. It is attributed to microwave excitation of the chiral Luttinger liquids of the edge states of the $p/(2p \pm 1)$ FQHE series. However, what are the electronic processes? how to understand the excitations? and how to think through in terms of the bizarre particles of CF's? are questions still under intense current theoretical debate.

1.2 Microwave induced cyclotron harmonies

It is well known from Kohn's Theorem that excitation by the electromagnetic radiation at the cyclotron frequency harmonics is not allowed in a translationally invariant electron system, and no harmonics of microwave cyclotron resonance has been observed. It is therefore a great surprise that giant microwave induced change in the dc resistance, $\Delta R/R$ of up to 250% were observed at the 2D electron cyclotron resonance frequency and its harmonics in our high

mobility samples in the 4-40GHz frequency range. This change in resistance is proportional to the square root of the microwave power. Investigations focusing on the physical origin of this effect and the potential for its use in detector application are being continued.

1.3 Pinning mode of the Wigner crystal

The sharp microwave resonance observed in the high B filed induced insulating phase of the 2D electrons in high quality GaAs/$Al_xGa_{1-x}As$ heterostructures, which we reported a few years ago, was a great surprise and an enigma. The insulating phase has long been expected to be a pinned Wigner crystal, and it would be natural to attribute the resonance to its pinning mode. However, the B field dependence of the resonance frequency is opposite to that expected and pinning by random disorder should not give rise to a sharp resonance.

This mystery is now solved by our new experiments on higher quality and lower density 2D electron samples, grown by Dr. Loren Pfeiffer of Bell Labs, which have made it clear that the insulator is indeed a pinned Wigner solid, showing the expected behavior of decreasing resonance frequency, f_{pk}, with increasing B ($B = (n_s/\nu) * 4.14 \times 10^{-7}$G-cm^2 in Fig. 2.

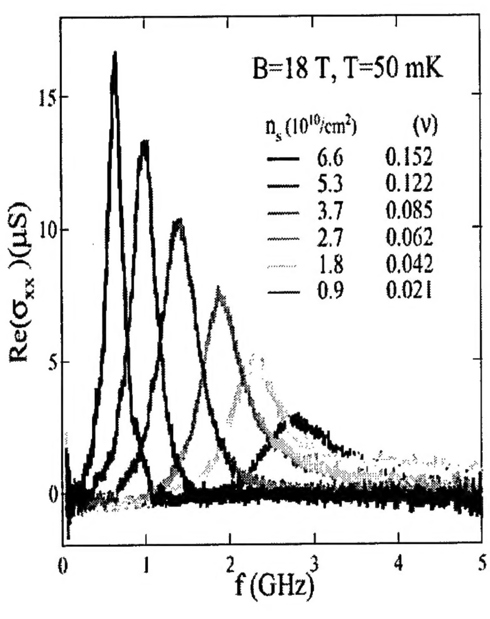

Fig. 1 Microwave resonance in in Re σ_{xx} vs f

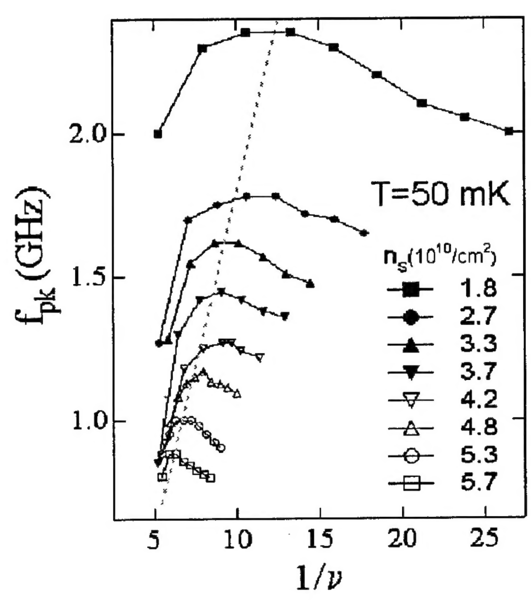

Fig. 2 Resonance frequency, f_{pk} vs $1/\nu$

The resonance is the pinning mode of the electron solid. But, the physics is much richer than having been expected. It turns out that the expected B filled dependence is that of the classical limit, only now accessible in the lowest density samples. In the earlier experiment, the classical

limit is inaccessible and the observed B field dependence of the resonance frequency reflects the pinning of the quantum crystal where exchange interaction is important. The sharpness of the pinning is now understood as a characteristic of the long range Coulomb force by the electrons, which correlates the guiding center motion of the electron lattice in the randomly pinned domains.

Fig. 1 shows the resonance at different densities varied by the gate voltage on the device, and Fig. 2 summarized data on the B field dependence of the resonance frequency. For B higher than that indicated by the dotted line in Fig. 2, the system approaches that of a classical 2D electron solid.

2. JOURNAL PUBLICATIONS

2.1) "Giant Microwave Photo Resistance of Two-dimensional Electron Gas, " P.D. Ye, L.W. Engel, D.C. Tsui, J.A. Simmons, J.R. Wendt, G.A. Vawter, and J.L. Reno, Applied Phss. Lett., **79**, p. 2193 (2001).

2.2) "High Magnetic Field Microwave Conductivity of 2D Electrons in an Array of Antidots," P.D. Ye, L.W. Engel, D.C. Tsui, J.A. Simmons, J.R. Wendt, G.A. Vawter, and J.L. Reno., Phys. Rev. B, **65**, 121305 (R), (2002)

2.3) "Correlation lengths of Wigner crystal order in a 2D electron system at high B fields," P.D. Ye, L.W. Engel, D.C. Tsui, R.M. Lewis, L.N. Pfeiffer, and K. West, Phys. Rev. Lett., **89**, 176802 (2002).

3. PERSONNEL

3.1 P.D. Ye (now member of technical staff at Agere Systems),

3.2 R.M. Lewis

3.3 Yong Chen